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CHARACTERIZATION OF RECYCLED CONCRETE FOR USE AS PAVEMENT BASE MATERIAL

by

Brandon James Blankenagel

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Brandon James Blankenagel

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	W. Spencer Guthrie, Chair
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Date	Grant G. Schultz

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As chair of the candidate's graduate committee, I have read the thesis of Brandon J. Blankenagel in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

CHARACTERIZATION OF RECYCLED CONCRETE FOR USE AS PAVEMENT BASE MATERIAL

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Master of Science

The use of recycled concrete material (RCM) as pavement base material is a promising but unproven technique for road rehabilitation and construction. A telephone survey conducted to investigate the state of the practice concerning RCM usage in Utah County revealed that RCM is infrequently used in this application due primarily to a lack of practical knowledge about the engineering properties of the material. Therefore, this research was aimed at evaluating the physical properties, strength parameters, and durability characteristics of both demolition and haul-back sources of RCM available in Utah County for use as pavement base material.

The study included extensive laboratory and field testing. Laboratory tests included California bearing ratio (CBR), unconfined compressive strength (UCS), stiffness, freeze-thaw cycling, moisture susceptibility, abrasion, salinity, and alkalinity evaluations. Non-destructive testing was utilized in the field to monitor seasonal variation in stiffness of an RCM pavement base layer over a 1-year period. The testing included a dynamic cone penetrometer, ground-penetrating radar, a heavy Clegg impact soil tester, a soil stiffness gauge, and a portable falling-weight deflectometer.

The laboratory testing indicated that the demolition material exhibited lower strength and stiffness than the haul-back material and reduced UCS loss after freeze-thaw cycling. However, the demolition material received a moisture susceptibility rating of good in the tube suction test, while the haul-back material was rated as marginal. Both materials exhibited self-cementing effects that led to approximately 180 percent increases in UCS over a 7-day curing period. Seven-day UCS values were 1260 kPa and 1820 kPa for the demolition and haul-back materials, respectively, and corresponding CBR values were 22 and 55. The field monitoring demonstrated that the RCM base layer was susceptible to stiffness changes due primarily to changes in moisture. In its saturated state during spring testing, the site experienced CBR and stiffness losses of up to 60 percent compared to summer-time values.

RCM compares well with typical pavement base materials in many respects. Given the laboratory and field data developed in this research, engineers should be able to estimate the strength and durability parameters of RCM needed for pavement design.

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CHAPTER 1
INTRODUCTION

The use of recycled concrete material (RCM) as a pavement base material is a promising but unproven technique for road rehabilitation and construction. This product has only recently entered the industry, becoming available in Utah County about 6 years ago. Some of the common sources of RCM include concrete pavements, bridge structures, and curb and gutter sections. At the end of their service lives, these infrastructure elements are demolished by various public or private contractors (*1*). RCM may also be generated from concrete over-runs or haul-backs associated with new construction (*2*).

Concrete producers and contractors traditionally seek out fill sites to dispose of demolished or excess concrete, which would otherwise be deposited in landfills. The present effort of the local industry to crush and sell the material as recycled concrete thus reduces the amount of waste sent to landfills and also provides an inexpensive alternative pavement base material (*1, 3*). RCM is roughly 25 percent less expensive per ton than conventional pavement base material in Utah County, giving a significant economic incentive to contractors and agencies alike to facilitate its use in pavement construction.

Recycled, crushed concrete may be used as aggregate in many applications, including new Portland cement concrete (PCC) pavement, bituminous concrete, lean-concrete or econocrete bases, pavement subbases, roadway shoulder material, bulk fill for drainage layers, rip-rap for erosion control, and bedding for utilities trenches (*1, 2, 4, 5, 6*). While success has been achieved in these applications, many agencies remain reluctant to permit its use as pavement base material because of the lack of engineering data on RCM properties and the variability in RCM associated with differences in composition and service history of the original concrete from which the RCM is derived (*4*). Therefore, this research focused on characterizing the strength and durability of

RCM produced from both demolition projects and haul-back concrete for use as pavement base material.

1.1 RESEARCH OBJECTIVES

The purpose of this study was to evaluate the physical properties, strength parameters, and durability characteristics of RCM relevant to pavement base material specifications and pavement design. Specifically, this research included evaluations of two sources of RCM available in Utah County, one produced from demolished concrete and the other produced from haul-backs associated with new concrete construction. Laboratory testing was conducted to assess the strength and durability characteristics of both sources, and a field study was performed to investigate the in-situ properties of RCM in a pavement structure.

1.2 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. Chapter 2 discusses the variability, self-cementing properties, leaching potential, and quality control and quality assurance (QC/QA) challenges associated with RCM. The experimental methodology utilized in the research is described in Chapter 3, including details of an informal telephone survey of Utah County engineers and contractors regarding their experience with RCM and the laboratory and field testing. Chapter 4 provides the survey findings and test results, and Chapter 5 gives a summary of research findings and recommendations for further research.

CHAPTER 2

PROPERTIES AND USE OF RECYCLED CONCRETE MATERIAL

The following sections summarize existing publications describing the variability, physical properties, self-cementing properties, leaching potential, and QC/QA challenges associated with the use of RCM as pavement base material. A brief description of documented uses of RCM concludes this chapter.

2.1 VARIABILITY

While the variability of RCM is naturally linked to the original ingredients utilized in different concrete mixtures, variability can also be introduced through different concrete construction practices that ultimately influence the quality of the hardened concrete. In particular, the effects of consolidation and curing can directly impact the physical properties of the concrete, including those that play important roles in the performance of RCM in pavement base layer applications (*2, 5*). For example, poorly consolidated concrete is characterized by an excessive amount of entrapped air that creates a more permeable pore system less resistant to damage under frost action (*2*). The increased absorption of poorly consolidated RCM will in turn correspond to higher optimum and in-situ moisture contents, on average, than other types of base materials. Another effect, inadequate curing, can yield concrete with reduced strength and thus reduced resistance to abrasion and impact. Insufficient soundness leads to mechanical degradation under normal construction operations, as well as to accelerated damage from freeze-thaw cycling. If the surface remains exposed to trafficking, an unsound RCM layer may also be susceptible to dusting over time.

In addition to variability associated with concrete mixture design and placement, variation in RCM particle-size distribution as a result of different crushing processes has also been noted. The relative amounts of coarse and fine fractions resulting from crushing can directly impact the self-cementing properties, density, permeability, and overall durability of the RCM. Variability in RCM properties can also impact bearing capacity and stiffness of RCM layers through the seasons (*1*, *2*, *3*, *5*, *6*, *7*, *8*, *9*). While various authors claim that specific crushing machines are better than others for achieving a desired distribution, the final particle-size distribution is also reported to be highly dependent on the crusher operator (*3*, *4*, *5*, *6*).

2.2 PHYSICAL PROPERTIES

American Society for Testing and Materials (ASTM) standards for evaluating granular fill materials have been utilized for characterizing RCM, but testing has mainly been aimed towards incorporating RCM in new concrete mixture designs. Testing procedures for RCM have typically included specific gravity, absorption, Los Angeles (L. A.) abrasion, and magnesium sulfate soundness testing (*4*, *5*, *6*, *7*, *8*, *9*). Deterioration of aggregates due to frost action and alkali silica reaction has also been evaluated (*2*). Table 2-1 presents results of specific gravity, absorption, and L. A. abrasion characterizations as reported by various authors. In all cases, RCM was found to have lower specific gravity and higher absorption values than typical crushed stone.

A couple of trends were noted by authors regarding absorption and specific gravity. According to Fergus, absorption greatly increases with decreasing particle size (*5*). Also, L. A. abrasion results are dependent on the strength of the original concrete, where stronger concrete breaks up less than weaker concrete (*2*).

TABLE 2-1 Properties of Recycled Concrete Material

Author	**Bulk Specific Gravity**		**Absorption (%)**		**L. A. Abrasion (%)**
	Coarse*	**Fine**	**Coarse***	**Fine**	
Hansen (*2*)	2.49	2.28	3.7	9.8	22 - 40
Fergus (*2*, *5*)	2.52	2.23	2.54	6.5	-
Chini (*4*)	-	-	-	-	26 - 37
Yrjanson (*5*)	2.4	2.2	4.3	5.9	20 - 45
Yrjanson (*5*)	2.45	2.36	3.31	6.45	-

*Coarse aggregate consists of particles retained on the No. 4 standard sieve.

Strength data for RCM used in pavement base layers are documented in just a few publications. Petrarca used the Benkelman beam deflection test to determine the structural capacity of RCM as a base layer and performed other tests to evaluate RCM for use as an aggregate in asphalt concrete (*10*). He concluded that RCM was more durable than typical materials and that degradation under handling was less than for typical crushed stone. Regarding compaction characteristics, Chini reported a maximum dry density (MDD) of 1917 kg/m^3 and an optimum moisture content (OMC) of 12.2 percent for RCM used as pavement base material in Florida (*4*).

2.3 SELF-CEMENTING EFFECTS

The American Association of State Highway and Transportation Officials (AASHTO) Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course gives some indication that the stiffness and strength of RCM increase with time, accompanied by a decrease in permeability (*11*). Both hydration and pozzolanic reactions can cause strength gain in recycled concrete (*12, 13*). The hydration reaction produces calcium-silicate-hydrate (C-S-H) and calcium hydroxide from water and the calcium silicate compounds comprising Portland cement. The pozzolanic reaction then combines calcium hydroxide with soluble silica and water to produce additional C-S-H, where soluble silica is usually provided as fly ash, silica fume, or slag. The pozzolanic reaction can only occur at pH levels above 10, which is the threshold at which silica becomes soluble (*14*). The reaction is useful because it essentially converts the relatively soluble calcium hydroxide into C-S-H, a more stable cementitious product that increases the strength and reduces the permeability of the resulting concrete (*12, 13*).

Although the formation of C-S-H enhances the strength and durability of concrete, its presence actually prevents complete cement hydration. As the hydration reaction proceeds, thickening layers of impervious C-S-H form around individual cement grains and effectively prevent additional water from reaching the unreacted cement remaining within the grains (*12, 13*). Also, the reduction in free water that occurs with continuing cement hydration yields a non-uniform pore-water system whose increasing tortuosity resists the equitable distribution of free water throughout the concrete matrix. As a result, some amount of unhydrated cement remains in almost all concrete structures.

When these structures are crushed, previously unhydrated cement can be exposed to new sources of moisture that lead to the formation of additional cementitious products through hydration reactions. Depending on the alkalinity of the RCM, pozzolanic reactions may also occur within the material as previously unreacted sources of soluble silica are exposed. The extent to which these reactions occur governs the degree to which self-cementing takes place. A more finely crushed RCM may therefore exhibit greater self-cementing than a coarser RCM because the increased surface area of the finer material allows more unhydrated cement grains to react with water.

2.4 LEACHING POTENTIAL

Some engineers have expressed concern regarding how RCM might affect the environment in which it is placed. RCM originating from highways and bridges in cold climates may have been subjected to deicing compounds that, over time, concentrated within the concrete structures (*7, 9, 11*). Yrjanson recorded chloride concentrations of 0.37 kg/m^3 to 0.68 kg/m^3 in Michigan RCM aggregate and concentrations of 0.31 kg/m^3 in fine RCM aggregate to 2.31 kg/m^3 in coarse aggregate in Wisconsin RCM (*2, 5*).

Such salts or other chemicals could be leached from RCM into the immediate environment. The tendency for leaching to occur is directly dependent on the availability of salt ions or other chemicals, the proximity of free water, and the moisture susceptibility of the RCM layer. Although C-S-H is generally considered to be stable and insoluble in the presence of water, calcium hydroxide is somewhat soluble (*12, 13*). Particularly in the presence of acid, calcium hydroxide can be readily dissolved, leading to increased concentrations of calcium ions and elevated pH levels in the concrete. In addition, calcium hydroxide can react with carbon dioxide in the air to form calcium carbonate, an inert but non-cementitious compound (*12, 13*). While this carbonation process reduces the available calcium and hydroxyl ions that may be leached, it also limits the amount of self-cementing that may occur in the RCM. If avoiding leaching is more important than ensuring self-cementing for a given project, deliberate pre-construction carbonation of the RCM may be appropriate.

Depending on the movement of pore water through the pavement structure and the extent to which carbonation occurs first, ions can be leached out of the RCM layer into the pavement subgrade and surrounding soils. If water percolating through the RCM layer is released at high pH levels into nearby streams or lakes, environmental damage may occur. Furthermore, the presence of high ion concentrations can accelerate corrosion of metal pipes buried in the vicinity of the RCM, as well as cause drainage blockages by precipitating in geotextile fabrics and other similar systems (*7, 11*). Despite these possibilities, RCM has been used successfully as drainage layers for pavements and buried utilities (*1, 2, 5, 9*).

Water flowing into and out of the pavement accelerates leaching and compromises the durability of the affected layers. While tightly compacted pavement base layers with high density and low permeability are usually desirable for preventing water ingress and migration within the layer, materials with high matric suction and even moderate permeability can experience substantial water ingress. Matric suction is mainly responsible for the capillary phenomenon in aggregate layers, where the radius of curvature of the meniscus in a capillary tube is analogous to the radius of curvature of an air-water interface in an aggregate matrix, and the height of capillary rise to the magnitude of matric suction (*15, 16*). Because the geometry of the air-water interface in soils and aggregates is dependent to a large degree on the particle-size distribution of the material, the gradation of the RCM can be a governing factor determining the moisture susceptibility and leaching potential of the material.

2.5 QUALITY CONTROL AND QUALITY ASSURANCE

QC/QA activities should be based on specifications of materials properties. RCM proposed for use as pavement base material may be required to meet particle-size distribution, specific gravity, absorption, plasticity index, compaction, abrasion resistance, soundness, alkalinity, or other laboratory or field test requirements to ensure adequate performance. The RCM may also be subject to maximum permissible limits on deleterious or foreign materials, including brick, asphalt, wood, metal, and miscellaneous solid waste (*6, 11*).

Regarding field testing for QC/QA of RCM layers, the use of standard techniques can be difficult. In particular, the nuclear density gauge provides artificially high moisture readings in RCM (*17, 18*). The device operates by emitting “fast” neutrons that are thermalized upon contact with hydrogen atoms. Thermalized neutrons that return to the gauge are counted and used by the device to compute the gravimetric moisture content of the tested soil or aggregate (*19*). Because the neutrons are equally thermalized by interactions with hydrogen atoms present in free water and hydrogen atoms incorporated in cementitious hydrates, the nuclear density gauge cannot distinguish between free water and structurally-bound water present in RCM. For this reason, gravimetric water contents in RCM and cement-treated base materials are routinely over-estimated by a nuclear density gauge. To overcome this problem, calibration curves for materials bearing cementitious hydrates should be developed separately for QC/QA applications on individual projects. Alternatively, non-nuclear devices, such as a soil stiffness gauge (SSG), Clegg hammer, portable falling-weight deflectometer (PFWD), or similar devices, should be considered for measuring in-situ properties of RCM.

The AASHTO specification mentioned previously provides an alternative density assessment method that requires a series of nuclear density tests during compaction processes to determine a maximum density standard in the field for each lot where RCM is being placed (*11*). This method may be cumbersome and inefficient, thus deterring the use of RCM.

2.6 DOCUMENTED USES

The majority of research conducted on RCM is based on its use as aggregate in new concrete. In particular, RCM has been successfully utilized in PCC pavement reconstruction (*5*). However, only a few publications address the use of RCM as a pavement base material. Yrjanson reported the use of RCM in a number of PCC pavements between 1975 and 1986, both for coarse aggregate in the new concrete and as cement-treated base and subbase layers (*5*), while Chini reported that RCM was used as base course material in airport pavements in Florida (*4*). Beyond these limited reports, specific details regarding the performance of RCM as a pavement base course are generally absent from the literature. Also, all information reviewed in the literature was based on demolition RCM, leaving the engineering properties of haul-back RCM completely undocumented (*2*).

2.7 SUMMARY

A literature review was conducted to investigate the variability, physical properties, self-cementing properties, leaching potential, and QC/QA challenges associated with the use of RCM as pavement base material. The variability of RCM is attributable to differences in original concrete sources and crushing processes; the particle-size distribution achieved by crushing especially influences absorption, density, strength, and self-cementing properties of RCM.

The self-cementing property of RCM is largely unaddressed in the literature. Although the crushing process can expose previously unhydrated cement for reaction with new sources of water, the extent to which self-cementing occurs has not been documented. Research does suggest, however, that salts and other chemicals may be leached from RCM layers utilized in moist environments and that typical QC/QA instruments such as the nuclear density gauge may not perform satisfactorily in RCM.

Most research on RCM has been conducted with the goal of using it in new PCC. The use of RCM as pavement base material is mentioned by only a few authors, and specific information about the performance of RCM in this application is not given in those publications. Furthermore, the scope of past research is limited to strictly demolition sources of RCM; no research has been conducted on haul-back RCM.

CHAPTER 3
EXPERIMENTAL METHODOLOGY

The first step in this research was to determine the present state of the practice concerning the use of RCM in Utah County via a telephone survey. Material samples were then obtained, and several laboratory and field tests were performed to characterize the properties of RCM for use as pavement base material. The following sections provide procedural details of the telephone survey and laboratory and field experiments.

3.1 TELEPHONE SURVEY

An informal telephone survey of Utah County engineers, contractors, and recycled concrete producers was conducted during the summer of 2003 to investigate the state of the practice with respect to the utilization of RCM and to identify local sources of both demolition and haul-back RCM for laboratory characterization. City and county engineers and contractors were asked whether or not they had used RCM and, if so, how they had used it and how well it had performed. They were also asked how they conducted QC/QA of the RCM during construction. RCM producers were queried as to the source of their materials and the applications in which their customers typically use RCM. Material qualities were also discussed with these individuals.

3.2 LABORATORY EXPERIMENTATION

Laboratory experimentation was designed to evaluate the physical properties, strength parameters, and durability characteristics of both sources of RCM available in Utah County. Representative samples were obtained in sufficient quantities to facilitate the laboratory testing program. While one source originated exclusively from concrete demolition, the second source originated from haul-backs and over-runs associated with new concrete construction. Both materials were crushed and stockpiled by the suppliers in the fall of 2003. Samples were collected in the spring of 2004 directly from the stockpiles and returned to the Brigham Young University Highway Materials Laboratory for testing. Samples of the demolition and haul-back RCM sources were oven-dried and then separated over several sieve sizes to facilitate construction of replicate specimens. Several tests were then conducted on the two materials as described in the following sections.

3.2.1 Characterization Testing

The properties utilized to characterize each material included particle-size distribution, plasticity index, specific gravity, absorption, OMC, and MDD. A short description of each of the testing procedures used to obtain these properties follows.

Washed sieve analyses (ASTM D 422) were performed to assess the particle-size distribution of the tested samples, and Atterberg limits tests (ASTM D 4318) were used to determine the plasticity of the samples. The limits, classified by flowability (liquid), cohesion (plastic), and shrinkage that occur at high, medium, and low moisture contents, respectively, are reported as the gravimetric moisture percentage corresponding to the given limit. If a material does not exhibit a plastic limit, it is classified as non-plastic. The results of the washed sieve analyses and Atterberg limits tests were used to relate RCM to other soils in the Unified and AASHTO soil classification systems.

Specific gravity and absorption tests were conducted to further characterize the materials. Specific gravity relates the apparent density of the material to that of water and was performed in general accordance with ASTM D 792. Absorption, a measure of the percent by mass of water that a given material contains in the saturated-surface-dry condition, was determined according to ASTM D 854.

The OMC and MDD were determined for each material. Specimens were constructed from the previously sieved RCM samples. The relative proportions of material retained on each sieve size were calculated to match the original gradation of the total sample, except that particles retained on the 19-mm sieve were discarded during sample preparation. Water was added in various percentages to several identical samples, and the moistened materials were allowed to equilibrate for 24 hours before being compacted using modified Proctor compaction energy. The weights and volumes of each freshly compacted specimen were measured before the specimens were oven-dried at 110°C until reaching constant weight. The gravimetric moisture content and dry densities were then computed and plotted. Data from five specimens were used to create a moisture-density curve for each material. The maximum point on this curve determined the OMC and MDD for each material.

3.2.2 Strength Testing

Strength evaluations included three basic tests. CBR was assessed after a 7-day cure, and unconfined compressive strength (UCS) and stiffness tests were performed daily throughout a 7-day curing period to assess strength gain with time. In each case, specimens were constructed in plastic cylindrical molds supported within a rigid metal sleeve to prevent buckling of the plastic mold walls during compaction. The following sections provide details for each of these tests.

3.2.2.1 California Bearing Ratio

CBR testing was conducted following ASTM D 1883 for laboratory-compacted soils. The test relates the bearing capacity of the material being tested to that of a standard crushed gravel. Three specimens from each source were prepared according to ASTM D 1557 in 152-mm-diameter plastic molds to a height of 116 mm. The specimens were allowed to cure at 100 percent relative humidity for 7 days before the test was performed. No soaking period was utilized so as to match the specimen conditioning procedures used for strength and stiffness testing. Figure 3-1 shows a specimen in the mechanical press. The specimen was positioned on a spacer plate within a metal cylinder, and an overburden weight was placed on top of the specimen. The face of the compression piston loaded the specimen surface through an access hole in the overburden plate.

FIGURE 3-1 California bearing ratio testing.

3.2.2.2 Unconfined Compressive Strength

UCS test specimens were compacted in 102-mm-diameter plastic molds in order to facilitate handling between compaction and UCS testing and then cured at 100 percent relative humidity. At the time of testing, the plastic mold was carefully removed with a small cutting tool as shown in Figure 3-2. Each specimen was then prepared by capping the ends with high-strength gypsum. Specimens were tested in a computer-controlled mechanical press at a constant strain rate of 1.3 mm/minute. As shown in Figure 3-3, a floating base was used to ensure that the applied load was evenly distributed over the specimen ends even when the caps were not exactly parallel. Three replicate specimens of each material were tested daily throughout a 7-day curing period.

FIGURE 3-2 Removal of plastic mold.

FIGURE 3-3 Unconfined compressive strength test using floating head.

3.2.2.3 Stiffness

Stiffness was measured using a free-free resonant column apparatus, in which the resonant frequency is used together with specimen length and density to compute Young's modulus for the material. Three specimens of each material were subjected to stiffness measurements throughout a 7-day curing period. These specimens were compacted inside 102-mm-diameter plastic molds with four 16-mm-long metal screws installed through the bottom of the mold from the outside, one in each quadrant approximately 30 mm from the center, as shown in Figure 3-4. Although the compacted lift thickness exceeded the height of the screw points exposed in the bottom of the mold, care was taken before compaction of the first lift to ensure that large aggregates were evenly distributed and well-seated around the screws rather than leaning on them. The container provided confinement for the specimens during handling, and the screw heads served as attachment points for an accelerometer equipped with a small magnet to be affixed to the base of each specimen during stiffness testing. Following compaction, the specimens were cured at 100 percent relative humidity throughout the testing period.

FIGURE 3-4 Specimen mold for stiffness testing.

In the test, a specimen was elevated on a metal stand, from which it was acoustically isolated by a ring of styrofoam insulation as shown in Figure 3-5. An accelerometer was attached to one of the four screws on the bottom, and a hammer equipped with a load cell was used to lightly tap the specimen surface. If a well-seated large aggregate was not exposed and available as a strike location, a small square aluminum plate measuring 25 mm by 25 mm by 2 mm was placed on the specimen surface to serve as a striking plate for the hammer. A strike of the hammer caused stress waves to propagate down through the specimen, and the accelerometer then measured the amplitude and frequency of the waves. A computer display of the measured wave response was used to determine the quality of a test run, and the average of nine measurements was used to compute Young's modulus for the specimen. The nine readings corresponded to three measurements with the accelerometer on each of three different screws. Equation 3-1 was used for calculation of Young's modulus (*20*).

FIGURE 3-5 Specimen stand for stiffness testing.

$$E = \gamma \left(\frac{2 \cdot f \cdot L}{1000} \right)^2 \qquad (3\text{-}1)$$

where $E =$ Young's modulus (Pa)

$\gamma =$ Density (kg/m^3)

$f =$ Resonant frequency (Hz)

$L =$ Specimen length (mm)

3.2.3 Durability Testing

Durability was evaluated using a number of tests that produced information about the physical, electrical, and chemical properties of the material, including freeze-thaw cycling, the tube suction test (TST), L. A. abrasion testing, salinity, and alkalinity. These tests are explained in the following sections.

3.2.3.1 Freeze-Thaw Testing

The resistance of RCM to damage when subjected to freeze-thaw cycling was measured according to ASTM D 560 with a 48-hour cycle length, except that performance was assessed by monitoring stiffness using the free-free resonant column rather than weight loss caused by wire brushing. In preparation for this test, three specimens of each material were compacted in specially prepared plastic molds. Each 102-mm-diameter mold was prepared by drilling 1.6-mm-diameter holes around the perimeter, as illustrated in Figure 3-6, to facilitate moisture transfer through the mold walls. Four holes were also drilled through the bottom of the mold, screws were inserted through these holes as described in the previous section, and the moistened sample was compacted on top of the screw ends exposed inside the container to ensure adequate mechanical coupling between the screws and the specimen. Specimens were cured for 7 days at 100 percent relative humidity, submerged in water for the last 4 hours of the curing period, and then sealed in plastic bags to begin the cycling period. The 4-hour soak, which established high moisture contents before the specimens were frozen, ensured a rigorous test. Stiffness measurements were taken midway through and at the end of each cycle in order to assess the durability of the specimens after each freezing and thawing period.

Each freeze-thaw cycle consisted of 24 hours of freezing at temperatures below –29ºC and 24 hours of thawing at temperatures above 20ºC. As shown in Figure 3-7, specimens were sealed in plastic bags, except when stiffness measurements were being taken, to prevent moisture loss due to evaporation. Also, specimens were submerged in water for the last 4 hours of each cycle in order to retain high moisture contents throughout the test. Stiffness measurements in the thawed state were taken after this 4-hour soak.

FIGURE 3-6 Specimen mold for stiffness testing during freeze-thaw cycling .

FIGURE 3-7 Freeze-thaw specimens in freezer.

3.2.3.2 Tube Suction Test

The TST, outlined in Texas Department of Transportation Test Method Tex-144-E, is a relatively new laboratory test designed to assess the moisture susceptibility of aggregate base materials. The moisture-susceptibility ranking is based on the mean surface dielectric value of compacted specimens after a 10-day capillary soak in the laboratory (*21*). The TST utilizes dielectric theory together with the principles of suction, permeability, and the state of bonding of water to assess the moisture susceptibility of aggregate base materials used in pavements.

RCM specimens subjected to the TST were scalped on the 19-mm sieve and compacted using modified Proctor compaction energy to a finished height of about 116 mm inside a 102-mm-diameter plastic mold. The plastic mold was prepared by pre-drilling 1.6-mm-diameter holes approximately 6 mm above the bottom of the mold at a horizontal spacing of 12.7 mm as shown in Figure 3-8. One hole was also drilled in each quadrant of the bottom of the mold about 30 mm from the center.

FIGURE 3-8 Specimen mold for tube suction test.

After a 7-day cure at 100 percent relative humidity, the specimens were dried at 60ºC for 3 days to less than 50 percent of their compaction moisture. They were then placed in a 12-mm-deep bath of deionized water at room temperature for a 10-day soaking period. The shallow water bath was enclosed in an ice chest to prevent water evaporation and to ensure a constant temperature and relative humidity during the test. The surface dielectric value was monitored daily during the soaking period using an Adek Percometer. At each measurement time, five dielectric readings were taken around the perimeter of the sample and a sixth in the center. The highest and lowest readings were discarded, and the remaining four were averaged. The final average dielectric value was used to rate the moisture susceptibility of the sample.

For materials with high matric suction and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix, leading to higher dielectric values at the surface. Non-moisture-susceptible materials, on the other hand, maintain a strong moisture gradient throughout the test, with little moisture reaching the surface, and have lower dielectric values at the end of the TST.

The interpretation of TST results is based on an empirical relationship between the final dielectric value and the expected performance of aggregate base materials (*21*). Aggregates whose final dielectric values in the TST are less than 10 are expected to provide superior performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible. Laboratory tests have confirmed a positive correlation between the TST moisture susceptibility classifications and the strength loss and frost heave characteristics of pavement base materials (*22*, *23*).

Upon conclusion of the 10-day soaking period, a moisture profile was determined by measuring the gravimetric moisture content of the top, middle, and bottom of each specimen. To enable calculation of water contents, samples were oven-dried at 110ºC until reaching constant weights.

3.2.3.3 Los Angeles Abrasion

A sample of each material was subjected to the L. A. abrasion test according to ASTM C 131. This test was developed for characterization of aggregates for concrete mixture design, but as the results apply to the construction industry in general, the test is used in specifications for pavement base materials as well. A 5-kg sample of each RCM source was prepared according to Grading B. The test required that each RCM sample be placed with 11 steel spheres inside a metal drum that rotated at a speed of approximately 30 rpm for 500 revolutions. The weight loss of the sample, in percent, was measured after the tested sample was washed over a standard No. 12 sieve and oven dried at 110°C.

3.2.3.4 Salinity and Alkalinity

Salinity and alkalinity were assessed using electrical conductivity and pH measurements, respectively. Electrical conductivity is a measure of the ability of a material to sustain electrical current flow. In soil media, this behavior is usually dominated by electrolytic current flow, which depends on the water content and salinity of the material. For assessment of this property, 5.0 g of oven-dried material passing the 0.425-mm sieve was placed in 100 g of de-ionized water for equilibration and monitoring over a 21-day period using a dual platinum-plate, contacting-type sensor. During the equilibration period, salts in the tested materials dissolve and increase the ion concentration of the solution, thereby increasing its electrical conductivity.

Measurements of pH were also taken on the samples used for electrical conductivity testing. Due to the presence of hydroxide ions, concrete typically has a pH greater than 10. Increasing quantities of free lime in RCM would therefore cause increasing values of pH.

3.3 FIELD EXPERIMENTATION

An evaluation of seasonal variability in RCM properties was conducted at a field site near Utah Lake. The following sections describe the field site, testing schedule, and test methods employed in this research.

3.3.1 Field Site

A parking area located near the east side of Utah Lake was constructed in 2004 using RCM as both the wearing course and structural layer over the soft natural subgrade. This parking area was used as a field site to monitor the strength and stiffness of in-situ RCM and to evaluate variability in these properties during seasonal changes. The natural subgrade in this area is a very soft, fine-grained material composed of lake sediments. The property owner selected RCM for this application due to its ability to effectively distribute loads over the low-strength subgrade. The parking area was constructed by placing a geotextile on the subgrade and compacting 200 mm to 300 mm of RCM as an initial wearing surface until a recycled asphalt surfacing could be placed. Compaction of the RCM was achieved by driving a loader with a full bucket of material over the graded RCM layer. The RCM for this parking area was produced from demolished concrete and was purchased by the property owner from the same supplier from which the laboratory sample was obtained for this research. However, the particle-size distribution appeared coarser, characterized by particle sizes as large as 76 mm. A meaningful evaluation of particle-size distributions would have required sampling at multiple locations throughout the test area, which was not permitted since the RCM material was already graded and compacted when the testing began.

3.3.2 Testing Schedule

The parking area was constructed in May of 2004, and testing was conducted in June, July, and August of 2004 and May of 2005. These test dates were chosen in order to monitor seasonal variation of RCM in the field. Because site monitoring did not begin until a month after the material had been placed, the testing was not designed to assess the extent to which self-cementing may have occurred; instead, it was intended to monitor in-situ strength and stiffness values of RCM at different times during the year. Therefore, 11 test stations 9.1 m apart were established in a straight line along the roadway following the southeast boundary of the parking area to facilitate repeated testing at the same locations.

By May of 2005, the recycled asphalt pavement layer had been placed. Therefore, readings taken on this date were offset laterally about 5 m from the original stationing in the roadway to an area where the RCM was still uncovered. Stations 3, 4, and 6 were not accessible after being offset, however, because vehicles were parked in long-term storage over these locations. Measurements on this date reflected the stiffness of the RCM layer in a fully saturated state, as frequent rain storms had soaked the site for several weeks prior to the day of testing.

Testing included layer thickness, CBR, and stiffness determinations. Layer thickness was determined using a dynamic cone penetrometer (DCP) and ground-penetrating radar (GPR). DCP readings were also used to determine CBR values. Stiffness was measured using three instruments: a heavy Clegg impact soil tester (CIST), an SSG, and a PFWD. Also, Atterberg limits tests were performed on the subgrade material.

3.3.3 Layer Thickness

The DCP shown in Figure 3-9 was used to determine the RCM layer thickness and to estimate in-situ CBR values by analyzing the penetration rate through each layer. In this test, a 25-mm-diameter cone was driven into the ground via successive blows of an 8-kg slide hammer dropped over a vertical distance of 57.5 cm. The depth of penetration was recorded along with the number of blows administered. The number of blows between

FIGURE 3-9 Dynamic cone penetrometer.

penetration readings was adjusted during the testing to ensure an adequate measurement density through the full profile. For this site, the number of blows between readings was typically two. DCP measurements were taken during each visit to the site, and care was taken to ensure that readings were not taken at identical locations so as to avoid measuring at previously disturbed areas.

While DCP data provided point estimates of the RCM layer thickness, GPR was used to evaluate the uniformity of the RCM layer along the full length of the test line. The GPR instrument transmits an electromagnetic signal from one wire coil and measures the response through a second wire coil. The electromagnetic waves reflect and refract at material interfaces due to differences in dielectric values from one medium to the next. The reflected waves are processed by a computer on the instrument, and a visual plot is displayed on the computer screen in real time. Figure 3-10 shows the GPR instrument used in this research. As the RCM layer thickness was not expected to change through time, GPR images were acquired during only the first visit to the site.

FIGURE 3-10 Ground-penetrating radar.

3.3.4 California Bearing Ratio

DCP penetration rate, in mm per blow, was used to estimate CBR using Equation 3-2 (*24*). The penetration rate for calculations was determined for each station by discarding the penetration measurements corresponding to the top and bottom of the RCM layer and averaging the remaining intermediate values. This procedure effectively excluded readings taken at the near surface and those taken while the cone passed from the RCM layer into the subgrade.

$$CBR = \frac{292}{DCP^{1.12}} \tag{3-2}$$

where $CBR =$ California bearing ratio

$DCP =$ Penetration rate (mm/blow)

3.3.5 Stiffness Monitoring

The three instruments used to measure stiffness are described in this section. The heavy CIST, shown in Figure 3-11, measures the deceleration rate of an 18-kg hammer dropped from a height of 305 mm. The material is characterized by a Clegg impact value (CIV), where 1 CIV is equivalent to 10 times the gravitational acceleration rate. Four drops constitute one test, and the highest CIV is automatically reported on the electronic CIST display. Three tests were conducted at each station. This test was planned to be conducted during each visit to the site, but unexpected instrument problems limited data collection to June, July, and August of 2004.

FIGURE 3-11 Heavy Clegg impact soil tester.

Figure 3-12 shows the SSG in use at the field site. The SSG has a 10-mm-diameter ring-shaped foot that is positioned on a thin layer of moist sand placed over the test location. The foot vibrates at various frequencies for a period of 60 seconds, and a stiffness value is calculated and displayed based on the ground response. Three measurements were taken at each station. This test was conducted during visits to the site in August of 2004 and May of 2005.

FIGURE 3-12 Soil stiffness gauge.

The PFWD device, shown in Figure 3-13, imparted a 15 kN force distributed over a 305-mm-diameter foot positioned on the ground surface. The ground deflections were measured directly under the center of the foot, 457 mm from the center, and 610 mm from the center. Based on the measured deflections and RCM layer thickness at each test location, the stiffness, or resilient modulus, of each layer was backcalculated using BAKFAA, a computer software program available from the Federal Aviation Administration. Although backcalculation is a proven technique for determination of modulus values, the results are subject to some degree of processing error. Again, three measurements were taken at each station. This test was conducted only in July of 2004 due to instrument availability.

FIGURE 3-13 Portable falling-weight deflectometer.

3.4 SUMMARY

The experimental methodology utilized in this research included a telephone survey and extensive laboratory and field testing. The telephone survey was conducted during the summer of 2003, and the laboratory and field tests began in the winter of 2003 and were completed in the summer of 2005.

The primary objective of the telephone survey was to investigate the state of the practice concerning the use of RCM among agencies within Utah County. Laboratory evaluations included tests for characterization, strength, and durability. Field testing focused on assessing the level of variability in strength and stiffness of RCM through the seasons.

CHAPTER 4
RESULTS

The data presented in this chapter are based on a telephone survey and extensive laboratory and field testing. The telephone survey was conducted to investigate the state of the practice in Utah County as to the use of RCM in various applications. Laboratory and field tests were performed to evaluate the strength and durability of two sources of RCM available in Utah County. The following sections detail the research findings.

4.1 TELEPHONE SURVEY

Approximately half of the persons contacted in the telephone survey were intrigued by the potential uses of RCM but had no experience with it. Those who had used RCM indicated that typical applications included sidewalk base material and engineered fill for utility installations. Only two of the individuals indicated that the material had been successfully utilized in pavement structures. In one case, RCM constituted the base layer of an asphalt pavement, and in another case the material was used as a structural layer for an unpaved parking area. The use of RCM in the latter case is depicted in Figure 4-1.

Those who had used RCM were generally pleased with its performance. They reported that its ability to bridge unstable soils was especially appealing, and many observed that the material exhibited a self-cementing effect that offered increased strength over time. For this reason, one contractor routinely specifies the use of recycled concrete for construction in the vicinity of Utah Lake, where the soft lake sediments are characterized by high water contents and low bearing capacities.

FIGURE 4-1 Unpaved recycled concrete material field site.

When utilized for pavement base layers, RCM is typically required to meet the same specifications as a standard road base material, and the same standard methods of QC/QA are applied. However, many of the survey participants observed that the properties of the material can vary with each delivery and that the nuclear density gauge usually gives incorrect readings in recycled concrete. These comments reflect the inherent variability of both demolition and haul-back sources of the material and the experience of others who have published on this topic (*17*). Variability in source materials is an important factor in recycling processes and appears to be a primary reason for the relatively low usage of RCM in Utah County.

4.2 LABORATORY TEST RESULTS

The following section describes the laboratory test results, including material characterization, strength properties, and durability.

4.2.1 Material Characterization

Material characterization tests included particle-size distribution, Atterberg limits, specific gravity, absorption, and moisture-density relations. Figure 4-2 gives the particle-size distributions from the washed sieve analysis for both RCM sources, which indicate that the haul-back material has considerably more medium and fine particles than the demolition material. This difference in gradation is probably attributable to differences in the crushing operations used by the suppliers, but it could also be due to differences in the mechanical degradation tendencies of the two materials (*4*). Haul-back material, having never been properly consolidated and cured as concrete, would likely have higher porosity and lower strength than the demolition material, which would result in greater pulverization of the haul-back material even if the same crushing operation were used.

The results of Atterberg limits testing indicate that both materials are non-plastic, consistent with the findings of other researchers (*4*). Both sources were classified by the Unified and AASHTO classification systems as shown in Table 4-1, in which specific gravity and absorption are also reported. The absorption values obtained in this research are typical of results obtained by other researchers for RCM.

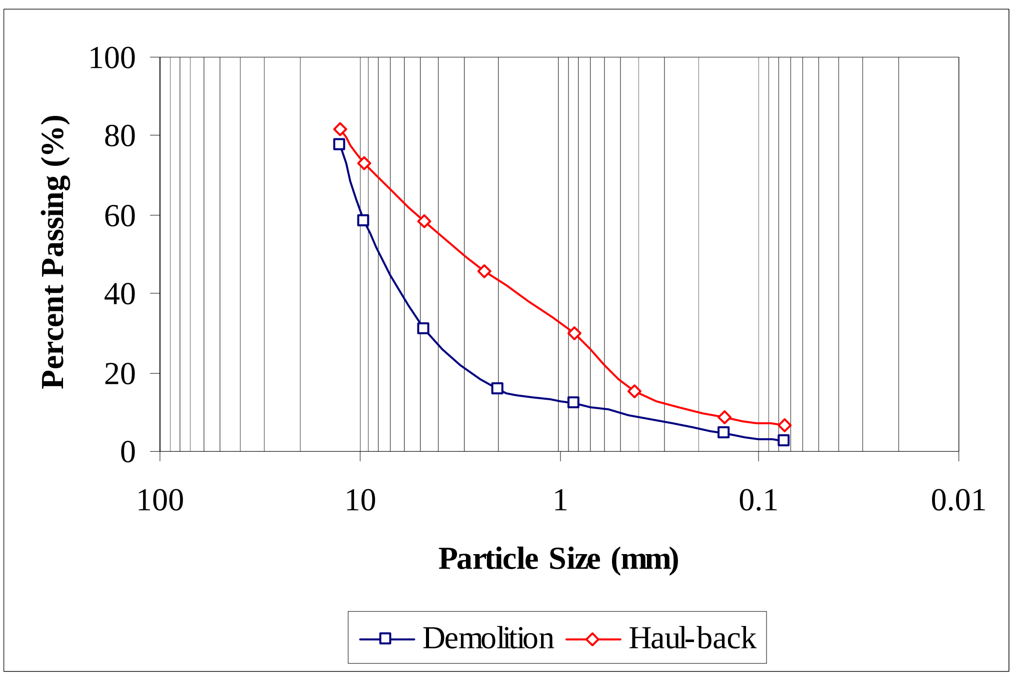


FIGURE 4-2 Particle-size distribution curves.

The specific gravity values in Table 4-1 represent the apparent specific gravity, which is always higher than the bulk specific gravity more commonly used in concrete mixture design and reported in the majority of the literature addressing RCM (*2, 4, 5, 7*).

The MDD and OMC values were derived from the moisture-density curves displayed in Figure 4-3. The demolition material had an OMC of 9.7 percent and a MDD of 1830 kg/m^3, while the haul-back material had an OMC of 10.6 percent and a MDD of 2020 kg/m^3. The higher OMC and MDD of the haul-back material correspond to its higher fines content. The finer particles fill in pore spaces, creating a denser matrix than the coarser demolition material. As reported in Chapter 2, the OMC computed by Chini for RCM was slightly higher at 12.2 percent, but the MDD of 1920 kg/m^3 for the material he tested is centered within the range of MDD values determined for RCM in this research (*2*).

TABLE 4-1 Recycled Concrete Material Characterization Summary

Source	Plasticity Index	USCS	AASHTO	Specific Gravity	Absorption (%)
Demolition	NP	GP	A-1-a	2.59	5.2
Haul-back	NP	SP	A-1-a	2.66	6.5

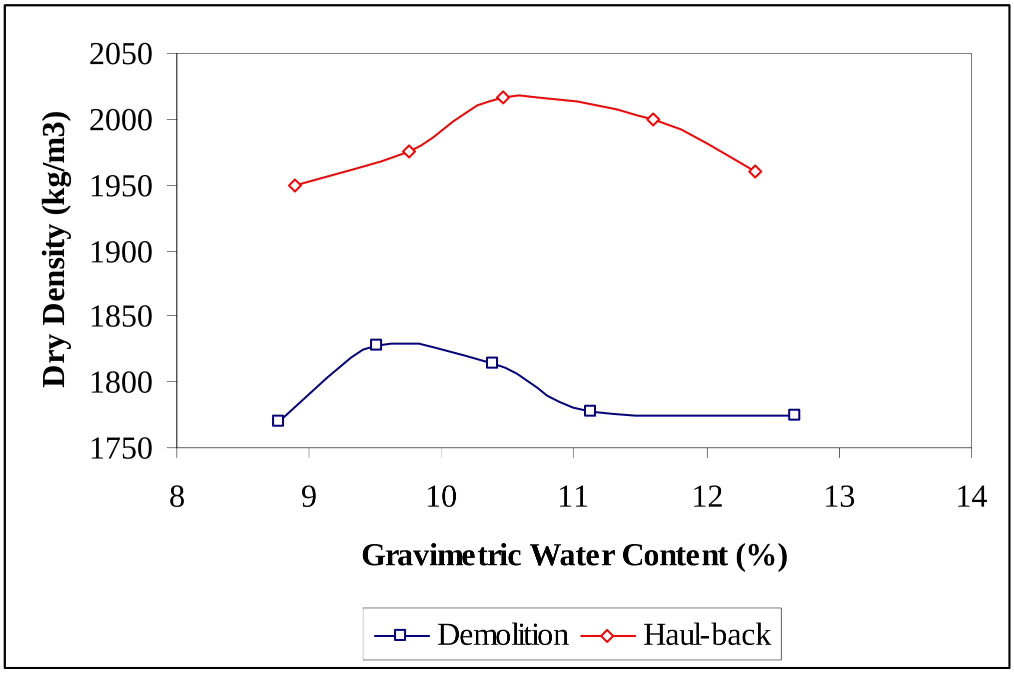


FIGURE 4-3 Moisture-density curves.

4.2.2 Strength Properties

Strength evaluations included CBR, UCS, and stiffness measurements. The results of these measurements are reported in the following sections.

4.2.2.1 California Bearing Ratio Test Results

The results of the CBR tests are reported in Table 4-2. The CBR values were determined by comparing the loads sustained by the test specimens at piston penetrations of 2.54 mm and 5.08 mm with the loads sustained by a standard crushed gravel at the same penetration depths. The average CBR values for the demolition and haul-back materials were 22 and 55, respectively, with corresponding standard deviataions of 3.5 and 6.1. Moisture contents averaged 8.1 percent for the demolition specimens and 6.1 percent for the haul-back specimens at the time of testing, which coincided with a 7-day curing period.

TABLE 4-2 California Bearing Ratio Measurements

Source	Specimen	CBR (%)
Demolition	1	22
	2	25
	3	18
Haul-back	1	62
	2	51
	3	52

4.2.2.2 Unconfined Compressive Strength Test Results

The UCS test results are shown in Figure 4-4. The demolition material experienced increases in strength of 130 percent from 0 to 3 days and 180 percent from 0 to 7 days. The haul-back material exhibited increases of 150 and 190 percent over the same periods. This increased strength over time confirms that self-cementing did occur in each sample, presumably due to hydration of cementitious components present in the recycled concrete samples. While the percent increases in strength were similar, the haul-back material had a UCS 70 percent greater than the demolition material throughout the 7-day curing period. This is likely due to the finer gradation of the haul-back material, which facilitated greater surface area for hydration reactions and a denser aggregate matrix. Average 7-day strengths were 1260 kPa and 1820 kPa for the demolition and haul-back materials, respectively, with corresponding standard deviations of 197 kPa and 38 kPa.

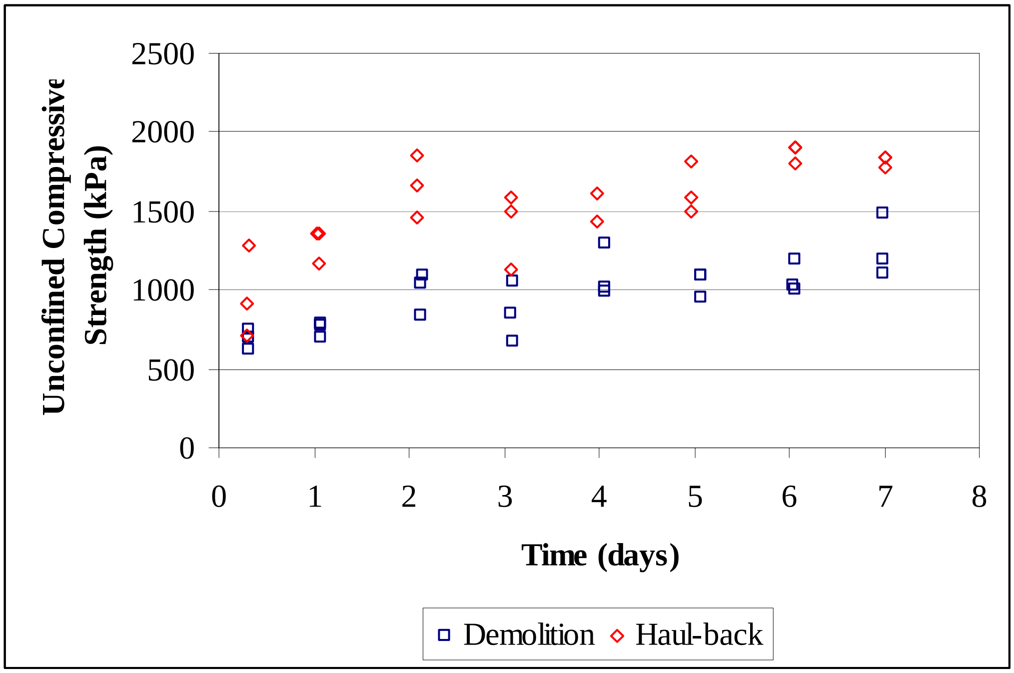


FIGURE 4-4 Unconfined compressive strengths.

4.2.2.3 Stiffness Test Results

Stiffness from the free-free resonant column test is reported in terms of Young's modulus as shown in Figure 4-5. Increases in modulus in the first 12 hours were 390 percent for the demolition material and 940 percent for the haul-back material. As these specimens were all cured at 100 percent relative humidity, the increase in stiffness was not due to drying, but is attributable to the self-cementing properties of the RCMs. The greater stiffness gain of the haul-back material compared to the demolition material can be attributed to the finer gradation of the haul-back material. As mentioned earlier, increased amounts of fines provide greater overall surface area and thus greater reaction rates for the previously unhydrated cement grains within the haul-back RCM.

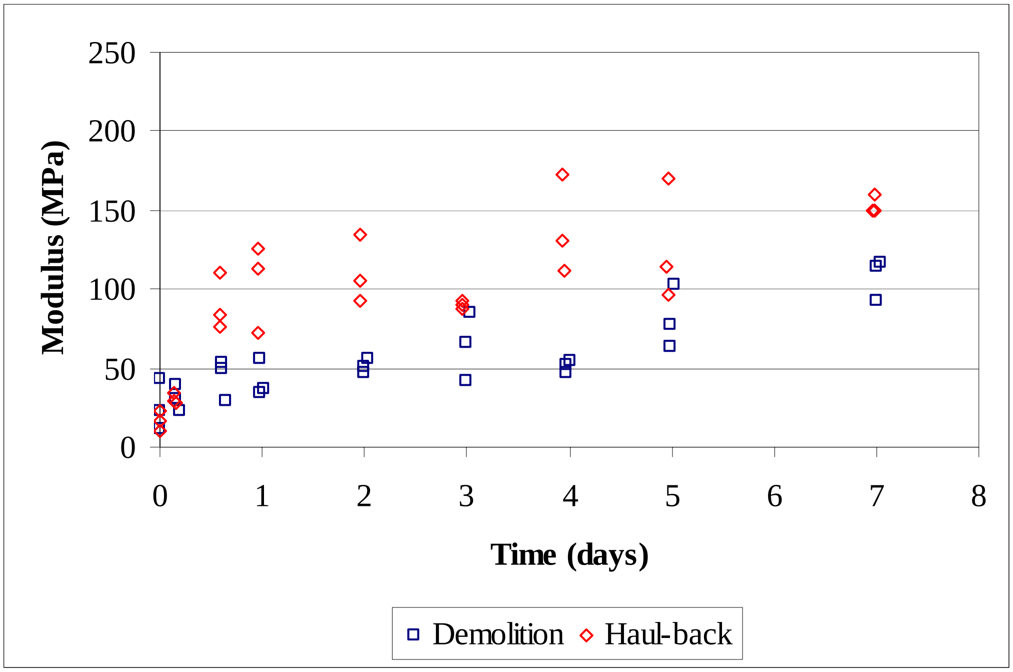


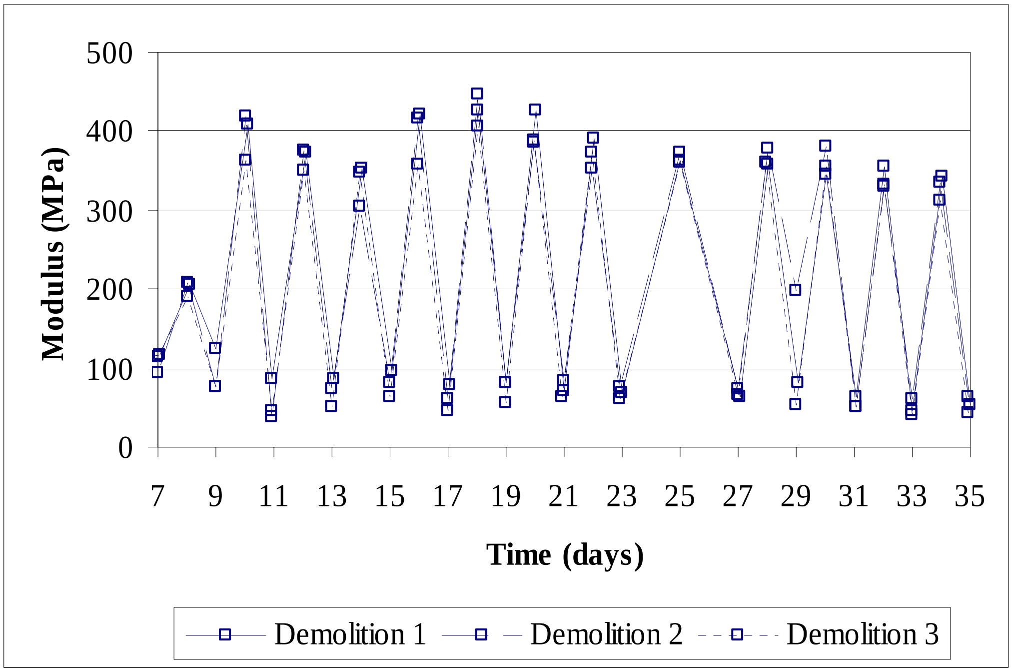
FIGURE 4-5 Modulus values from stiffness testing.

4.2.3 Durability

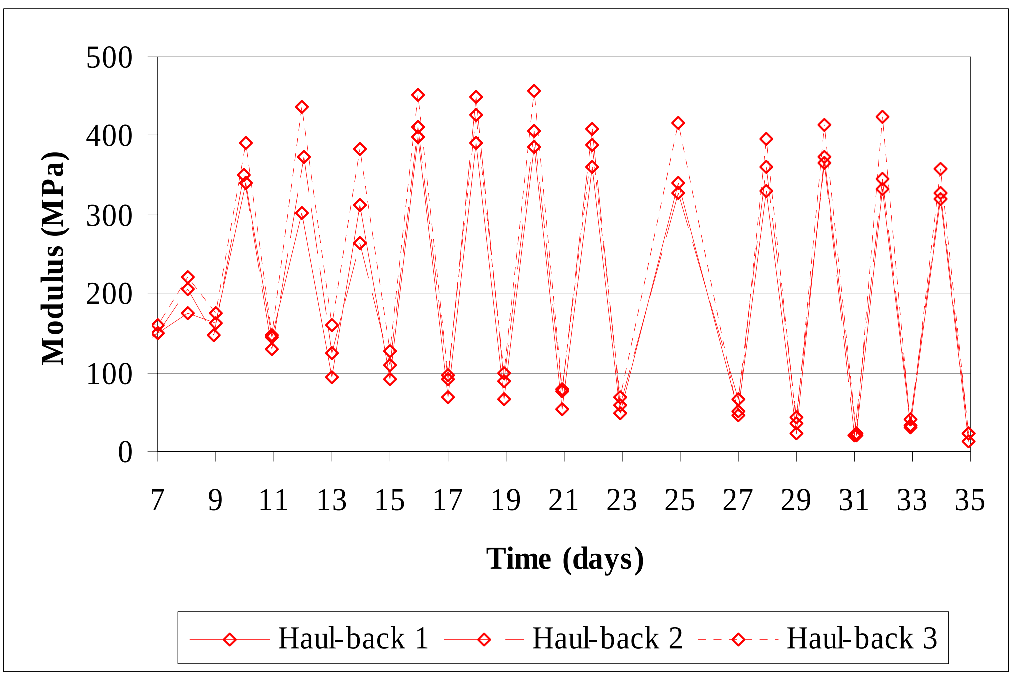
Durability evaluations included freeze-thaw testing, TST measurements, L.A. abrasion testing, salinity determinations, and alkalinity measurements. The results of these tests are presented in the following sections.

4.2.3.1 Freeze-Thaw Test Results

Figure 4-6 shows stiffness data collected throughout the freeze-thaw testing period. As explained in Chapter 3, the two materials began the freeze-thaw cycling after 7 days of curing. The cluster of 8-day modulus readings corresponds to the end of the first freeze, and the 9-day modulus readings correspond to a thawed and saturated state achieved at the end of the first 48-hour cycle. Each cluster of modulus readings thereafter corresponds to half of a cycle.



(a) Demolition material.



(b) Haul-back material.

FIGURE 4-6 Modulus values of frozen and thawed recycled concrete material.

Generally, the modulus values decrease with time, indicating breakdown of the specimens. The demolition material experienced a 30 percent stiffness loss within the first two cycles and stabilized at a residual stiffness of about 70 MPa throughout the remainder of the testing. The haul-back material experienced a 90 percent stiffness loss over the first nine cycles before stabilizing at a residual stiffness of about 30 MPa. The modulus value after the second freeze was approximately twice that measured after the first freeze, which suggests that aggregate breakdown was sufficient in the first freeze to allow specimens to imbibe much more water during the second soaking period. Upon freezing, the additional absorbed water increased the overall stiffness of the specimens.

The freeze-thaw specimens were subjected to UCS testing after completion of the freeze-thaw cycling. The ultimate strengths averaged 610 kPa for the demolition material and 1300 kPa for the haul-back material, with corresponding standard deviations of 45 kPa and 333 kPa. Moisture contents for the specimens at the end of testing averaged 11.9 percent and 10.4 percent for the demolition and haul-back materials, respectively. These strengths are much lower than the 7-day strengths of the specimens cured uninterrupted at 100 percent relative humidity, with 52 percent and 28 percent strength losses for the demolition and haul-back materials, respectively. These data indicate that strength losses did not match stiffness losses, particularly for the haul-back material. Table 4-3 summarizes the results of freeze-thaw cycling.

TABLE 4-3 Freeze-Thaw Test Results

Testing Result	Source	
	Demolition	Haul-back
Original 7-day stiffness (MPa)	108	153
Residual stiffness (MPa)	70	30
Overall stiffness loss (%)	35	80
Cycles before meeting residual stiffness	2	9
7-day control unconfined compressive strength (kPa)	1260	1816
Final unconfined compressive strength (kPa)	610	1300
Final gravimetric moisture content (%)	11.9	10.4
Strength loss compared to 7-day control (%)	52	28

4.2.3.2 Tube Suction Test Results

During the 10-day TST, dielectric values were measured daily and are plotted in Figure 4-7. The demolition material received an overall good rating with an average final dielectric value of 6.4 and an average final gravimetric water content of 10.6 percent. The haul-back material received a marginal rating with an average final dielectric value of 15.0 and an average final gravimetric water content of 10.2 percent. The final moisture profiles are shown in Figure 4-8. The demolition material maintained a moisture gradient during the test, with comparatively little moisture reaching the surface, while the haul-back material developed relatively uniform moisture profiles by the end of the soaking period. If the haul-back material were to be used in a high-type highway facility, chemical stabilization or some other form of aggregate improvement would probably be required to improve the material to a non-moisture-susceptible condition.

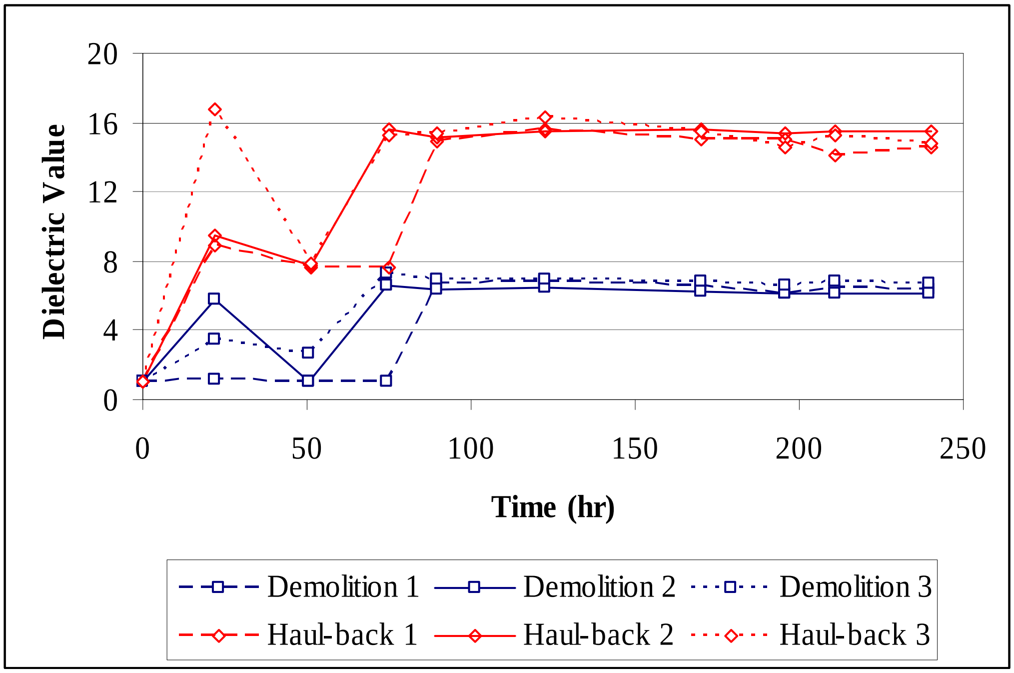
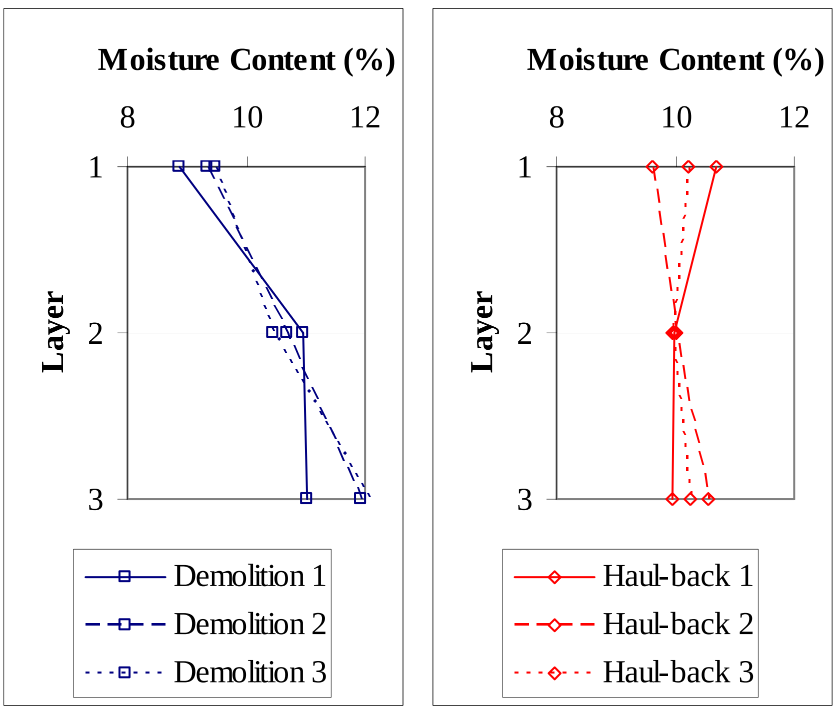


FIGURE 4-7 Tube suction test dielectric values.



(a) Demolition **(b) Haul-back**

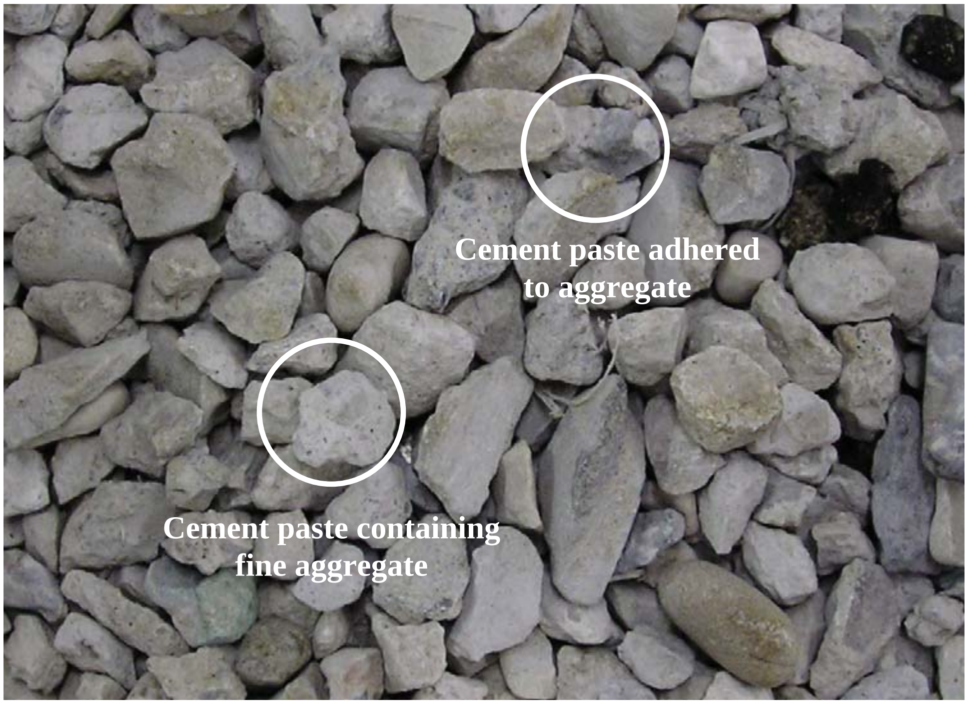
FIGURE 4-8 Moisture profiles at conclusion of tube suction test.

4.2.3.3 Los Angeles Abrasion Test Results

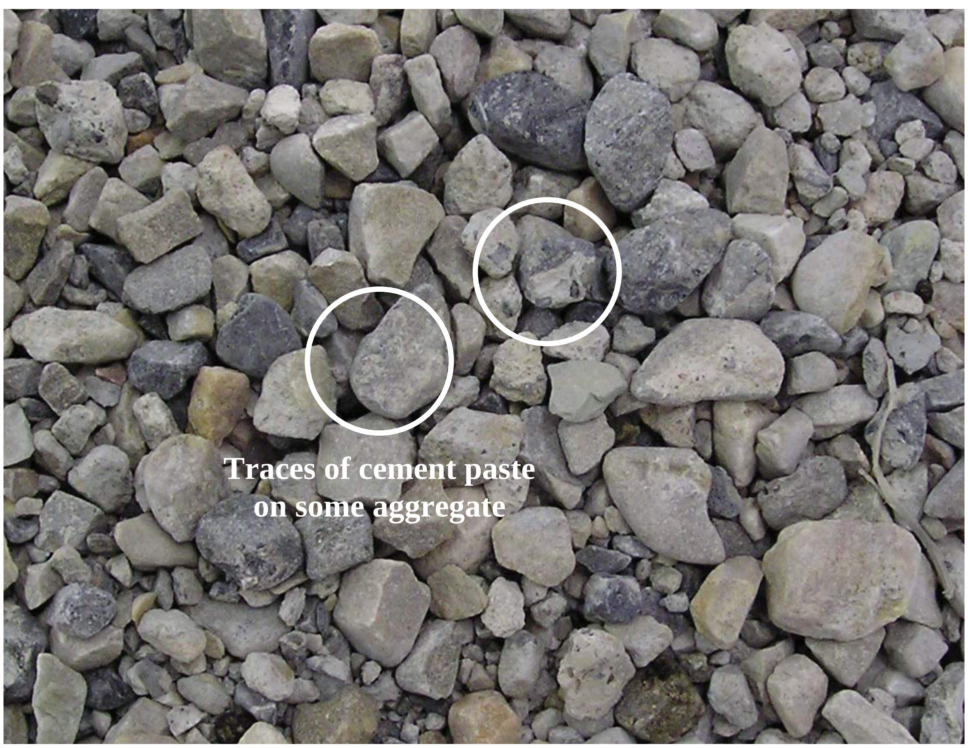
Aggregate weight losses for both of the materials in the L. A. abrasion test are similar to the values reported by other researchers. The demolition and haul-back materials experienced 31 percent and 17 percent losses, respectively. Upon completion of the test, both materials had been nearly stripped of cement paste so that the aggregates appeared comparatively clean. This was especially true for the haul-back material as shown in Figure 4-9.

The breakdown of cement paste during construction processes is possibly more beneficial to the material than it is detrimental. As explained in Chapter 2, cement particles hydrate from the outside in, and when a sufficient layer of solid paste is formed around the yet unhydrated core, the hydration process slows significantly as the reaction becomes diffusion-controlled. When RCM particles are crushed, unhydrated cement is exposed and can begin hardening upon re-hydration. Hydration of the newly exposed cement is the basis for the self-cementing effect exhibited by RCM materials.

A disadvantage of particle breakdown is that the percentage of fine particles is increased. In the case of the demolition material, the change in particle-size distribution would likely increase the MDD, but where the haul-back material already has a significant percentage of fines, further increases in fines may prove detrimental to the stability and moisture susceptibility of the RCM.



(a) Before Los Angeles abrasion test.



(b) After Los Angeles abrasion test.

FIGURE 4-9 Degradation of haul-back recycled concrete material.

4.2.3.4 Salinity and Alkalinity Test Results

Salinity and alkalinity were assessed using electrical conductivity and pH measurements, respectively. Electrical conductivity measurements are graphed against time in Figure 4-10. Although electrical conductivity cannot be used to determine the concentrations of specific ions within multi-ion solutions, it is a reliable indicator of the ionic strength resulting from all ions in the tested solution (*25*). The elevated electrical conductivity of the haul-back material suggests a greater presence of ions than in the demolition material. Because the haul-back material was never actually placed in service, it would not have been exposed to deicing salts; instead, the source of the comparatively high electrical conductivity is probably the presence of calcium and hydroxide ions resulting from the presence of free lime. The exact origin of the demolition material is unknown, but the possibility exists that the original concrete was not subjected to deicing salts as would be a pavement or other exterior structure. The presence of deicing salts would likely lead to higher electrical conductivity measurements than observed in this research for the demolition material.

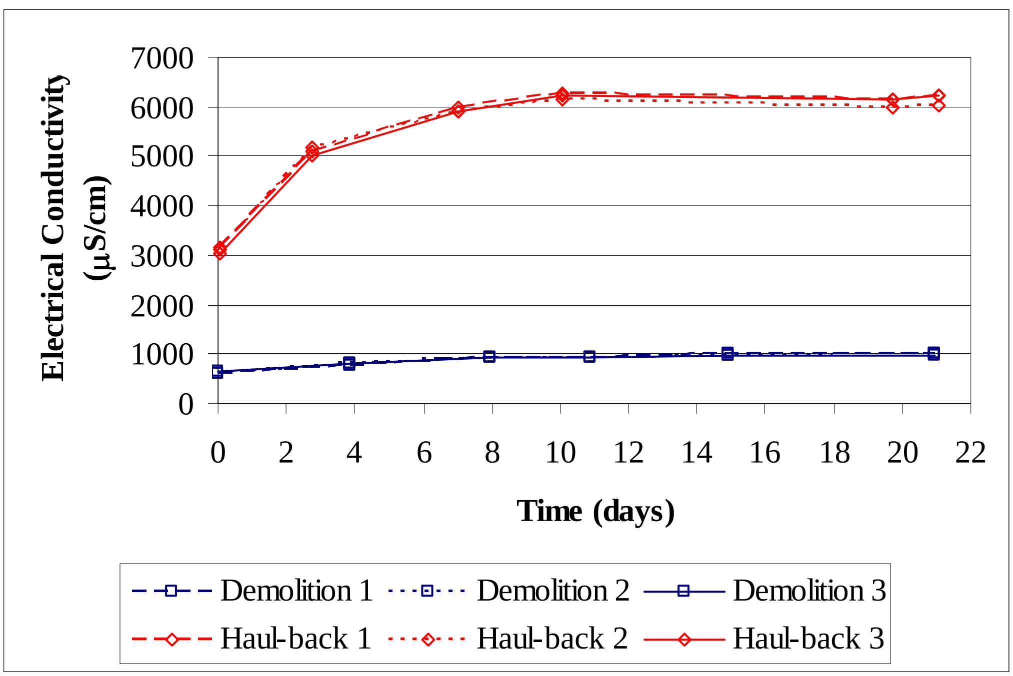


FIGURE 4-10 Electrical conductivity of solution specimens.

The pH measurements for the materials are given in Table 4-4. These pH values indicate a greater presence of hydroxide ions in the haul-back material than in the demolition material. The pH levels can influence the self-cementing behavior of the recycled concrete. The presence of free lime, for example, would increase the pH of the recycled concrete and potentially lead to pozzolanic reactions within the material that would supplement the hydration reactions (*14*). As mentioned in Chapter 2, not all of the cement may have hydrated before the concrete was crushed and stockpiled. Therefore, both pozzolanic and hydration reactions could be responsible for early-age increases in the stiffness and strength of RCM.

TABLE 4-4 Recycled Concrete Material Salinity and Alkalinity

Source	Solution Salinity (μS/cm)	Solution pH
Demolition	930	11.64
Haul-back	6200	12.87

4.3 FIELD TEST RESULTS

The layer thickness data, CBR calculations, and stiffness values measured during field testing are presented in this section.

4.3.1 Layer Thickness

The site profile was assessed using the DCP and GPR instruments as described in Chapter 3. Estimated from DCP data, the RCM layer thickness was determined as the depth at which the penetration rate dramatically increased. Figure 4-11 is a plot of the resulting RCM layer thicknesses computed using DCP data. The solid line represents the average of the three readings for each station. The depth ranged from 116 mm to 232 mm, with an average of 161 mm and a standard deviation of 42 mm. Variation among repeated measurements taken at a single site can be attributed to small thickness variations and a lack of precision associated with subjectively determining the depth at which the penetration rate increases.

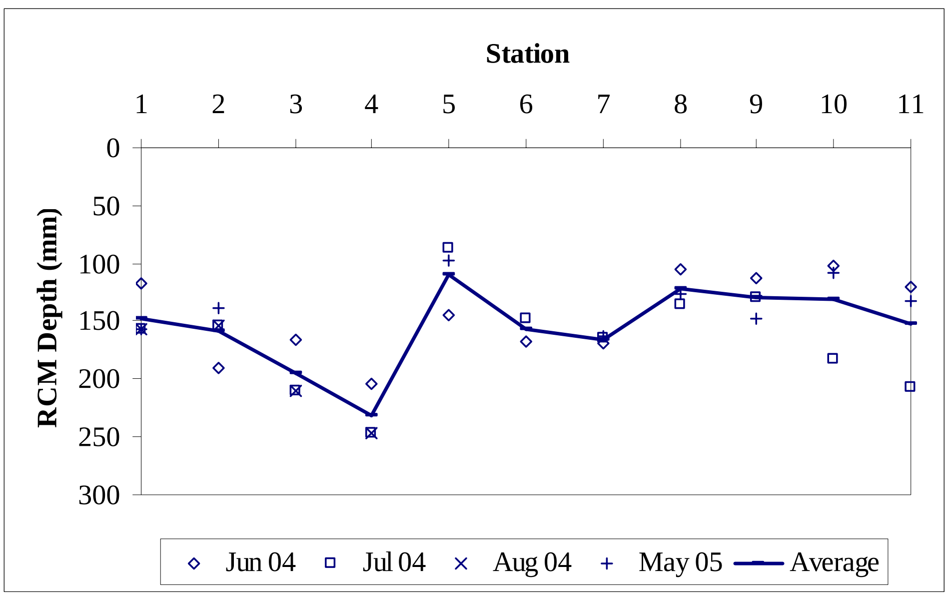
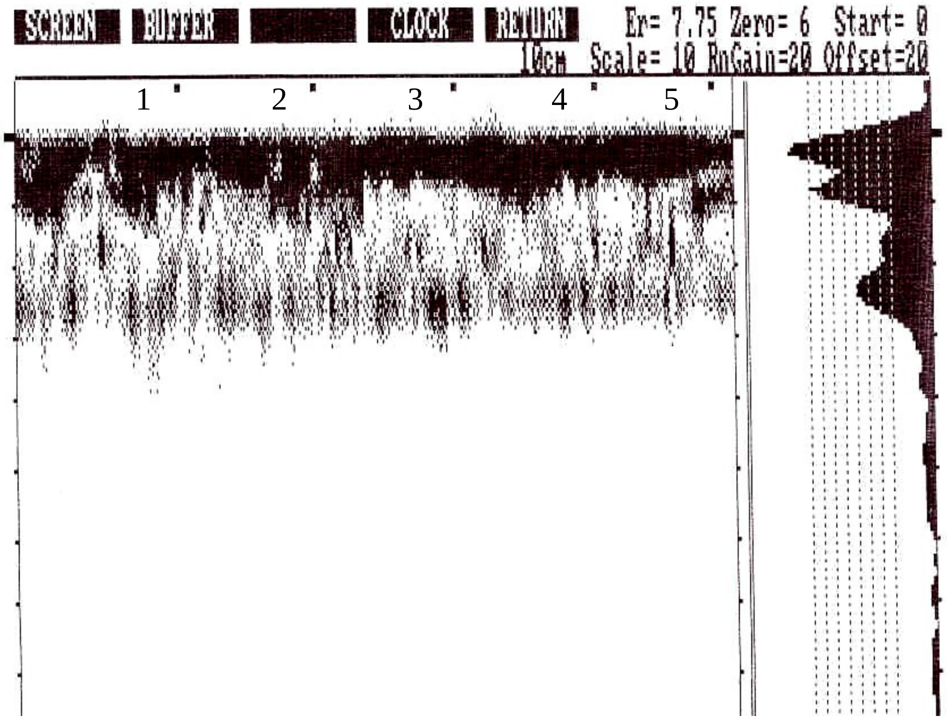


FIGURE 4-11 Recycled concrete material layer thickness.

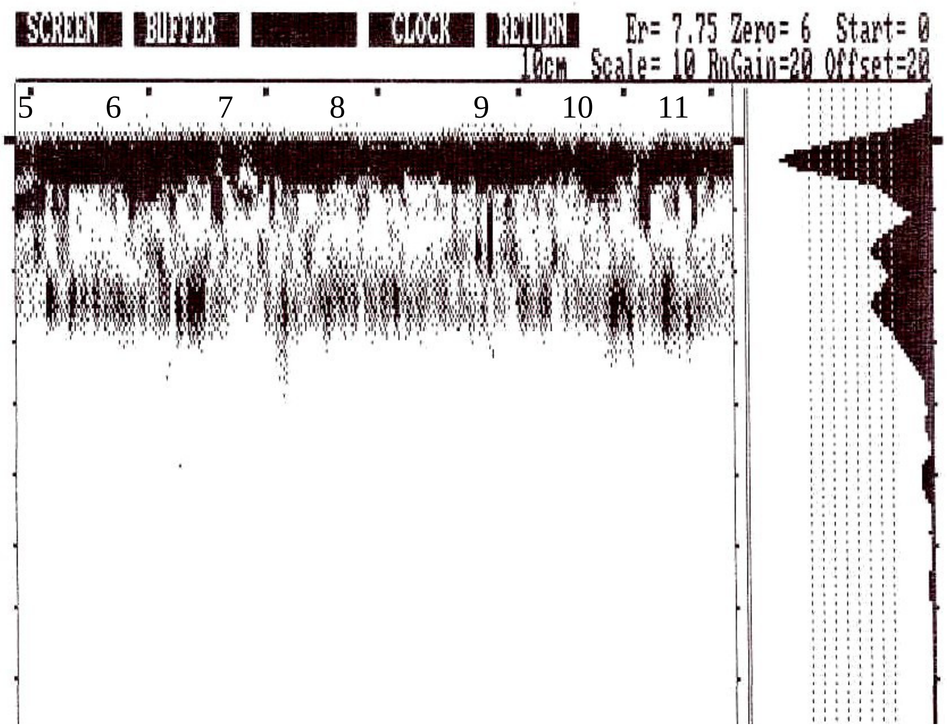
The continuity of the RCM profile was assessed using GPR. Figure 4-12 presents GPR images from station 1 to station 11. The readings were taken along the length of the site, and each of the square dots at the tops of the images represents a station. The dots spaced vertically on the sides of the images represent 305-mm depth increments. Layer depth can be estimated as the difference between the first and second reflections shown toward the top right side of each figure, where reflections are designated as dark peaks whose amplitudes decrease with increasing depth. Estimates of RCM layer depths determined from the GPR images are compared to the depths estimated from DCP data in Table 4-5. The R^2 value for a regression line relating the two sets of measurements was computed to be 0.47. The difference between DCP- and GPR-determined depths is greatest at station 6, although a reason for the discrepancy could not be identified.

Table 4-5 Layer Thicknesses Measured Using Dynamic Cone Penetrometer and Ground-Penetrating Radar

Station	DCP (mm)	GPR (mm)
1	144	150
2	166	200
3	196	200
4	232	225
5	116	125
6	157	225
7	167	150
8	120	150
9	122	175
10	143	150
11	163	150



(a) Stations 1 to 5.



(b) Stations 5 to 11.

FIGURE 4-12 Ground-penetrating radar images of field site.

4.3.2 California Bearing Ratio

The average DCP penetration rate for each layer was used to calculate the average CBR for each station using Equation 3-2. Figure 4-13 displays the resulting CBR values for both the RCM layer and the natural subgrade. The subgrade CBR values depicted in Figure 4-13 are the average values for each station for the months of June, July, and August. The mean subgrade CBR is 6.5, and the standard deviation is 2.7. The plasticity index of the subgrade was 14, which is consistent with the low strength of the material.

CBR values for 2004 correlate well with the laboratory-measured average CBR of 22 for this material. Figure 4-13 illustrates an increase in CBR in the first months after placement, presumably due to drying during the summer months; however, the values generally decrease to just below the initial CBR value upon saturation in May of 2005.

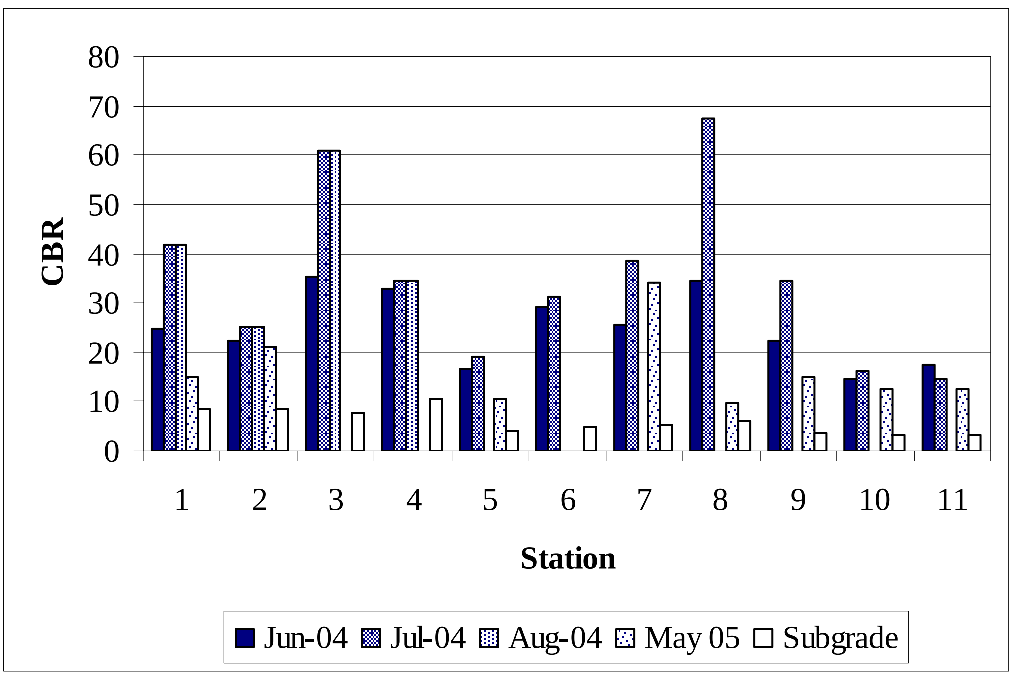


FIGURE 4-13 California bearing ratios of recycled concrete material and subgrade.

4.3.3 Stiffness

The RCM layer stiffness was measured using three different instruments, including the CIST, SSG, and PFWD. The CIST was used in June, July, and August of 2004. The mean CIV and standard deviation for each station are reported in Table 4-6. Due to equipment failure, not all of the stations were tested in June of 2004.

The SSG was used in August of 2004 and May of 2005. The mean stiffness values and standard deviations for each station are reported in Table 4-7. The August values are markedly higher than the May values. As mentioned previously, the field site was entirely saturated during May of 2005, with some locations inundated by standing water. The stiffness measurements were therefore much lower in May than in the other months.

TABLE 4-6 Clegg Impact Soil Tester Values

Station	Clegg Impact Value					
	June 2004		July 2004		August 2004	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
1	14.60	1.51	15.73	4.74	12.30	2.00
2	18.27	1.21	17.37	1.31	18.13	2.37
3	22.10	2.65	22.10	4.19	20.33	2.01
4	10.20	2.40	12.65	3.62	21.45	5.36
5	-	-	13.65	1.97	12.00	1.90
6	-	-	15.55	2.59	16.30	2.29
7	-	-	15.75	1.26	13.35	2.67
8	-	-	13.90	1.78	12.70	0.80
9	-	-	12.60	2.91	12.30	1.44
10	-	-	10.15	0.62	12.50	2.50
11	-	-	10.95	2.71	10.55	0.95

TABLE 4-7 Soil Stiffness Gauge Values

Station	Modulus (MN/m)			
	August 2004		May 2005	
	Average	Std. Dev.	Average	Std. Dev.
1	17.50	0.85	5.72	0.21
2	15.85	0.07	5.95	0.07
3	24.95	2.19	-	-
4	18.55	0.64	-	-
5	12.90	0.99	8.05	0.04
6	13.70	0.85	-	-
7	12.05	1.20	8.07	0.22
8	13.80	1.56	11.50	1.02
9	15.65	2.62	8.48	0.58
10	7.90	1.56	6.43	0.22
11	7.65	0.35	6.13	0.07

The PFWD was used only in August of 2004 due to its lack of availability in other months. The mean modulus values and standard deviations for each layer at each station are reported in Table 4-8. Generally, the RCM stiffness was several times greater than the stiffness of the subgrade. This was expected and is comparable to the observed differences in CBR between the layers.

TABLE 4-8 Resilient Modulus Backcalculated from Portable Falling-Weight Deflectometer Data

Station	Modulus (kN/m^2)			
	RCM		Subgrade	
	Average	Std. Dev.	Average	Std. Dev.
1	289	103	28	0.5
2	174	34	26	1.2
3	215	77	38	2.4
4	117	5	29	0.2
5	110	105	15	1.4
6	39	20	18	0.7
7	23	-	24	-
8	202	54	18	0.3
9	58	11	16	0.1
10	26	10	14	0.4
11	103	85	17	0.3

4.4 SUMMARY

The results are summarized in this section. The telephone survey is discussed first, followed by laboratory and field results.

4.4.1 Telephone Survey

The telephone survey provided valuable information concerning the use of RCM in Utah County. Many of the survey participants were not familiar with the material but were intrigued with the possibilities of using it. Those individuals who had used RCM expressed some concern with QC/QA issues and had thus limited its use to base material for sidewalks and low-volume roads and fill for utility trenches. The largest local RCM construction project identified in the survey was a parking area near Utah Lake, where RCM was used because of its ability to bridge the soft natural subgrade.

4.4.2 Laboratory Observations

Demolition and haul-back RCMs were classified as poorly sorted gravel and poorly sorted sand, respectively, in the Unified soil classification system, and both were classified as A-1-a in the AASHTO soil classification system. Specific gravity, absorption, OMC, and MDD were discovered to be within the typical ranges reported in the literature.

The strength of these materials was assessed in terms of CBR and UCS, and stiffness was measured using a free-free resonant column apparatus. CBR values measured after 7 days of curing at 100 percent relative humidity averaged 22 for the demolition material and 55 for the haul-back material. UCS values increased with curing time, illustrating the self-cementing properties of RCM. The demolition material experienced an increase in strength of 130 percent from 0 to 3 days and 180 percent from 0 to 7 days. The haul-back material exhibited increases of 150 percent and 190 percent over the same periods. Seven-day strengths were 1260 kPa and 1820 kPa for the demolition and haul-back materials, respectively. Stiffness measurements showed similar trends, with 7-day modulus values being 110 MPa and 150 MPa for the demolition and haul-back materials, respectively.

Durability was measured by monitoring the stiffness of RCM specimens subjected to freeze-thaw cycling and by evaluating the material in the TST, the L. A. abrasion test, an electrical conductivity test, and an alkalinity test. Freeze-thaw testing caused 30 percent and 90 percent stiffness losses in the demolition and haul-back specimens, respectively. The TST resulted in moisture susceptibility ratings of good for the demolition material and marginal for the haul-back material. L. A. abrasion losses were 31 percent and 17 percent for the demolition and haul-back materials, respectively. Electrical conductivity stabilized at averages of 930 μS/cm for the demolition material and 6200 μS/cm for the haul-back material. Measurements of pH were 11.64 and 12.87 for the demolition and haul-back materials, respectively.

While the two materials were classified similarly, differences in their particle-size distributions and original concrete sources caused significant differences in laboratory test results. The haul-back material exhibited greater strength and stiffness than the demolition material when uninterrupted curing was provided, and it also exhibited less strength loss after freeze-thaw cycling. However, the demolition material received a better moisture susceptibility rating in the TST than the haul-back material and exhibited less stiffness loss after freeze-thaw cycling. Although the availability of the two sources of RCM may ultimately determine which type will be used on a given project, these strength and durability data should be considered in the design of RCM pavement base layers.

4.4.3 Field Observations

RCM layer thicknesses and in-situ stiffness values were measured at a field site over a 1-year period in order to obtain measurements corresponding to seasonal variation. The RCM layer thickness within the testing area was measured using a DCP and GPR and varied in thickness from 100 mm to 250 mm. CBR values calculated from DCP data ranged from 15 to 65 during late summer, and these values correlate fairly well with laboratory-measured data. Stiffness was monitored with a heavy CIST, an SSG, and a PFWD. The site exhibited the lowest stiffness when it was in a saturated state during spring, with typical decreases between 30 percent and 60 percent compared to measurements obtained during late summer.

RCM compares well with typical pavement base materials in many respects. Given the laboratory and field data developed in this research, engineers should be able to estimate the strength and durability parameters of RCM needed for pavement design.

CHAPTER 5
CONCLUSION

The use of RCM as a pavement base material is a promising but unproven technique for road rehabilitation and construction. A telephone survey of local engineers and contractors indicated that RCM has not been frequently used as a pavement base material due primarily to a lack of practical knowledge about the engineering properties of the material. Therefore, this research was dedicated to classifying and characterizing both demolition and haul-back sources of RCM available in Utah County.

Extensive laboratory and field tests were performed to evaluate the strength and durability of the materials. Strength was assessed in terms of CBR and UCS, and stiffness was measured using a free-free resonant column. Durability was measured by monitoring the stiffness of RCM specimens subjected to freeze-thaw cycling and by evaluating the material in the TST, the L.A. abrasion test, a salinity test, and an alkalinity test. Seasonal monitoring of a field site constructed using demolition RCM utilized a DCP, GPR, a heavy CIST, an SSG, and a PFWD. The following sections present the findings of the research and design recommendations for pavement structures utilizing the material.

5.1 FINDINGS

Two local suppliers provided RCM samples for this research. The two RCM sources were classified as poorly sorted gravel and poorly sorted sand for the demolition and haul-back materials, respectively. Both materials were categorized as A-1-a in the AASHTO soil classification system. After a 7-day curing period, average CBR values were measured to be 22 and 55 for the demolition and haul-back materials, respectively, and corresponding 7-day UCS values were 1260 kPa and 1820 kPa. Seven-day modulus values were 110 MPa for the demolition material and 150 MPa for the haul-back material. Marked increases in strength and stiffness were noted for both materials during the first 2 to 3 days after compaction, attributable to the reaction of previously unhydrated cement with water to form new cementitious products. While both materials experienced strength and stiffness losses during freeze-thaw cycling, the haul-back material was slower to reach a residual stiffness than the demolition material, and its UCS loss after the testing was considerably less than that exhibited by the demolition material. However, the haul-back material received a moisture susceptibility rating of marginal in the TST, while the demolition material was rated as good.

The field monitoring demonstrated that the RCM base layer was susceptible to stiffness changes due primarily to changes in moisture. In its saturated state during spring, the site experienced CBR and stiffness losses of up to 60 percent compared to summer-time values. Stiffness values measured with the SSG showed similar losses.

Overall, RCM compares well with typical pavement base materials in many respects. Given the laboratory and field data developed in this research, engineers should be able to estimate the strength and durability parameters of RCM needed for pavement design.

5.2 RECOMMENDATIONS

While two distinct sources of RCM are represented in this research, the properties of any RCM will depend on its source and will likely vary to some degree from the values reported in this report. If the material is to be used on a high-type facility, laboratory testing should be performed to characterize the proposed RCM source. If the material exhibits unacceptable strength or resistance to moisture and frost damage, stabilization techniques are recommended to improve the properties of the RCM. As the free-free resonant column utilized in this research has not been previously used to monitor deterioration of laboratory specimens subjected to freeze-thaw cycling, further work is needed to develop threshold values by which the resistance of materials to freeze-thaw damage may be rated. In conjunction with the TST, this test may be used to assess the efficacy of stabilization for improving the durability of low-quality materials.

Self-cementation of RCM is a unique property attributable to the reaction of previously unhydrated cement with water to form new cementitious products. Further research is recommended to determine the relative impacts of original concrete mixture design, consolidation, curing, and crushing on the degree to which self-cementing occurs. Furthermore, although free lime can benefit strength gain, excessive concentrations of hydroxide ions may cause environmental damage if leaching of the free lime occurs. Further research should be conducted to evaluate the susceptibility of RCM to leaching.

The construction of reinforced concrete pavements over RCM base layers may also require special consideration with regards to leaching. If the concrete structure demolished to produce the RCM was subjected to high chloride concentrations during its service life, then the chlorides may become available to the overlying concrete pavement. Migration of the chlorides into the steel-reinforced concrete surface layer could lead to active corrosion of the reinforcing bars and subsequent cracking of the concrete slabs.

Highway structures require base layers that support the flexible or rigid wearing course. RCM exhibits strength and stiffness properties typical of materials commonly used for pavement base layers. Selection of RCM as a pavement base material would ultimately depend on agency preference and RCM availability and cost. While this research provides engineers with values of material properties needed for the design of RCM base layers, economic analyses must be conducted by the agency to optimize the overall pavement design.

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